Decomposition Analysis Resolution Process (DAR) of Systems Engineering Applied to Development of Countermeasure on Leakage of Engine Head-Gasket

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Abstract. This paper reviews a countermeasure development of leakage from coolant seals of head-gaskets in a diesel engine applying the Decomposition Analysis and Resolution Process (DAR). We can find complexity arising from some causes of leakage even in a simple square-ring rubber seal. The major causes are (1) large displacement around a head-gasket generated by the combustion, (2) seal distortion at a high compression, (3) seal rubber degradation induced by coolant microorganism deterioration, (4) uncontrolled seal production and (5) unsuitable rubber composition. Through our DAR, we can resolve the complexity of the leakage and can clarify all the cause positions and their relationships. We can confirm that an improved silicone rubber seal, which has a higher fatigue strength, an excellent acid-resistance and a uniform contact property, is the correct resolution. This paper also shows development of a hydrogenated nitrile rubber seal as a permanent measure, which can extend the Middle of Life (MOL) of Product Lifecycle Management (PLM) of the industrial diesel engine production.

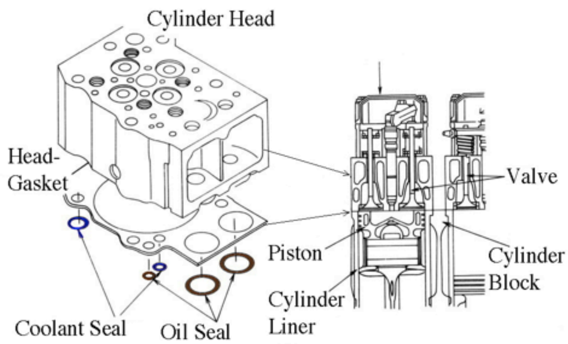
Keywords: DAR, PLM, MOL, engine, head-gasket, coolant, seal, leakage,

1 Introduction

The purpose of this paper is to describe importance of the DAR for resolving a problem of parts: head-gasket (antifreeze) coolant leakage. This paper also shows that the Middle of Life (MOL) of Product Lifecycle Management (PLM) [1] for an industrial diesel engine can be extended by a permanent measure, which is derived from the countermeasure development. A long-term MOL is required, because an industrial diesel engine is generally manufactured during 10-20 years like capital goods [2]. Extending the MOL of the engine production period leads to increase revenue, to reduce all the engine related costs and to obtain customers confidence.

Although a coolant seal is only a simple square-ring part, the leakage process has complexity. Fig. 1a) shows the configuration of the engine head-gasket and coolant seals. Coolant and oil galleries both in a cylinder block and cylinder heads are connected with each seal of the head-gasket. The head-gasket is a steel plane plate. The previous coolant seals adopted the same silicone rubber: Rubber-P, as those of oil seals. Within a year from its production, newly developed high-output diesel engines caused the coolant leakage from the head-gasket in the field. After dismantling all cylinder heads, unusual seal cracks were found as shown in Fig. 1b). Although the oil seals adapt the same Rubber-P, and have similar dimensions as those of coolant seals, the oil seals never caused oil leakage or a crack in the field. The cause of coolant leakage seemed to have complexity. Therefore, we have conducted thorough DAR for analyzing the complexity and for confirming appropriateness of the countermeasure.

Technical reports on this issue have published by the author as a transaction paper [3] of the Society of Automotive Engineers (SAE) and as a paper of Japanese technical magazine [4].



a) Schema of Engine Head-Gasket and Coolant Seals

b) Unusual Coolant Seal Crack

Fig. 1. Schema of Engine Head-gasket and Unusual Crack of Coolant Seal (Ohkawa S. et al. 1994 [4])

2 Approved baseline Requirements, CONOPS and DAR

Approved baseline requirements of the countermeasure are to develop a replaceable improved seal as soon as possible and to clarify the leakage mechanism. For agile repairing in the field, the engine-side modification like a cylinder head change was prohibited.

The CONOPSs of the coolant seal are to use from -50ºC to +110ºC, to have oil-compatibility and to keep 10,000 hours seal life. The CONOPSs limit rubber type only to a silicone rubber.

Fig. 2 summarizes all the critical issues of the coolant leakage as the DAR [5]. Every critical issue is discussed in the following sections from the top of the system to the bottom of material composition.

2.1 Methodology

To clarify the complexity of the unusual seal crack mechanism, we have conducted thorough investigations using following methodologies:

- Measurement of engine head-gasket temperature and distortion
- Observation/measurement of seal mechanical behavior and the seal rubber strength and microscopic observation of seal fracture
- Chemical analysis and microscopic observation of deteriorated seal rubber and deteriorated coolant both on biological and chemical effects
- Process check of seal manufacturer (quality control)
- Chemical and instrumental analyses of rubber composition.

All the methodologies are consistent with all the critical issues and heading titles from 2.2 to 2.6.

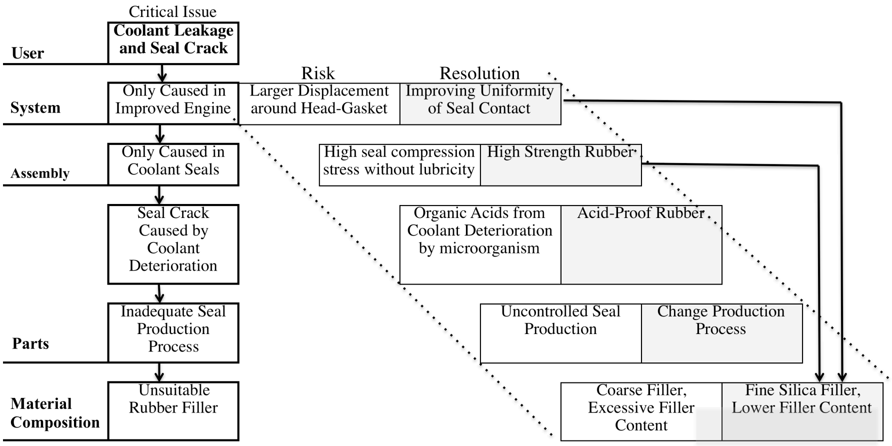


Fig. 2. Critical Issues of Coolant Seal Leakage

2.2 Leakage only Caused in High-Output Engine

It became clear that a larger distortion generates around the head-gasket by increasing engine output. Since the head-gasket temperature is preserved below the same 120 ºC as that of the previous engine at coolant seal positions, the seal temperature has no relation with the leakage.

Therefore, we investigated uniformity of seal contact at a higher compression condition. Fig. 3 shows a visual observation of seal contact condition on the engine cylinder block. A front square-ring seal: previous Rubber-P, generates air-bubbles on the square-ring surface because of seal distortion. Contrarily, a rear square-ring seal; candidate Rubber-S, does not cause air-bubble.

Fig. 4 shows upper limits of compression ratio up to the generation of unequal pressure distribution. The beginning of seal distortion was measured using a pressure measurement film. The Rubber-P has the lowest property on contact uniformity and causes distortion only at 28% compression. Since the seal compression range in the head-gasket is 20-40%, the Rubber-P and a Rubber-A (COTS) seals cause unequal contact in the head-gasket.

Fig. 3. Visual Observation of Silicone Rubber Seals Contact with Acrylic Resign Block: Simulated Cylinder Head (Ohkawa S. et al. 1993[4])

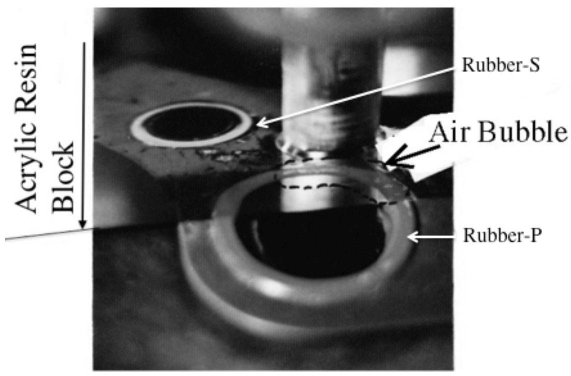
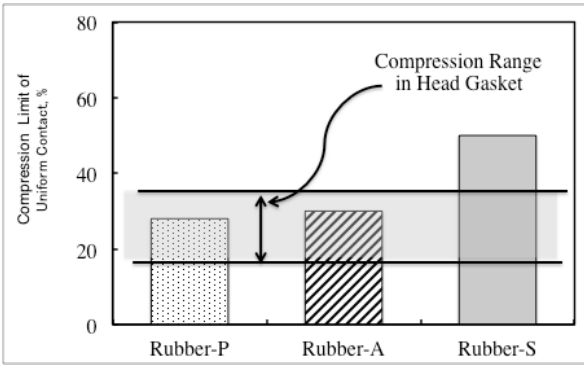


Fig. 4. Upper Limit of Compression Ratio for Keeping Uniform Contact



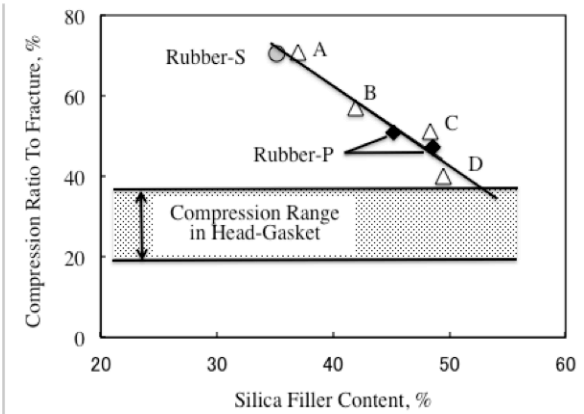
The candidate Rubber-S can keep uniformity of seal contact in the head-gasket.

2.3 Leakage Caused Only in Coolant Seal

In our measurement, a viscosity of a typical ethylene-glycol coolant is only 3-4% value of that of an engine oil at 80ºC. Therefore a coolant can easily leak from even in a narrow gap and has no lubricity. On the other hand, an engine oil can not pass through the gap and can lubricate seal surface. Lack of seal surface lubrication induces a high compression stress [6].

From our seal fracture observation, we clarified that the unusual seal crack is fatigue damage. Fig. 5 shows the results of seal compression fracture test on the Rubber-P, candidate Rubber-S and COTS's silicone rubbers (A to D). It is clear that the silica filler content has a relationship with the facture strength. Although the Rubber-Ps show lower facture compression ratios, the values are higher than the maximum compression ratio in the head-gasket. Therefore a seal fatigue test was planned as a verification test to reproduce the unusual crack. The Rubber-S and COTS Rubber-A show the highest fracture strength.

Fig. 5. Compression Fracture Test Results (ts: Seal thickness, tg: Head-gasket thickness) (Ohkawa S. et al. 1993[3]



2.4 Seal Crack Caused by Coolant Deterioration

In an emergency-use generator engine, the previous Rubber-P caused coolant leak and cracks after only 18 operating hours. The generator engine had long-term stoppages. The used coolant smelled of mold; microorganism. The rubber polymer was severely decomposed by organic acids. Table 1 shows the analytical data of used coolants in the generator engine and in a reference marine engine. Despite of short operating hours, the generator coolant contains excessive organic acids comparing with that of the marine engine. From these facts, it can be estimated that the organic acids were generated from a microbial degradation of ethylene-glycol. Tsuneki T. [7] indicates that bacteria propagate in a ethylene-glycol solution under 20% concentration. The concentration of the ethylene-glycol coolant in the generator engine was 15% by poor maintenance.

By immersion tests in an organic acid solution, we found that the candidate Rubber-S, which adopted an acid-proof polymer, shows lower degradation than that of Rubber-P. Dynamic sealing tests of acid immersed seals are planned for a verification test.

Table 1. Chemical Analysis of Organic Acids in Used Coolants

	Emergency Generator Engine 18 hrs (2 years)	Marine Engine 2,100 hrs (2 years)
Total Acid Ion, ppm	607	109

2.5. Inadequate Seal Production Process

Since a manufacturing failure of seals was also considered as a cause of unusual seal cracks, we conducted process check to the seal manufacturer. We found that the seals were manufactured in the 3rd sub-contractor and they did not conduct any quality control on rubber cure conditions (Fig. 6). Therefore, an engine quality assurance division soon changed this situation and ordered the seal supplier to conduct strict quality control of the seal production.

Despite the serious potential risk on previous seal quality, we could not find any seal quality problem in all the stock seals. The estimated potential risk is to cause the crack by lowering the rubber fatigue strength. We came to the conclusion that the process is not the cause of the unusual crack.

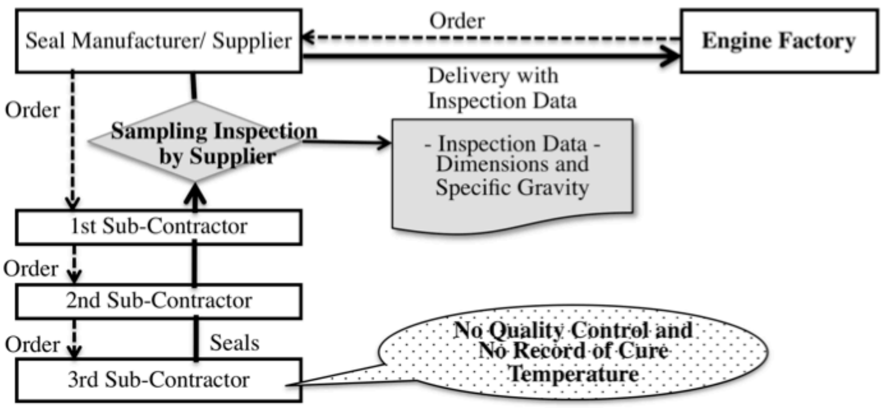


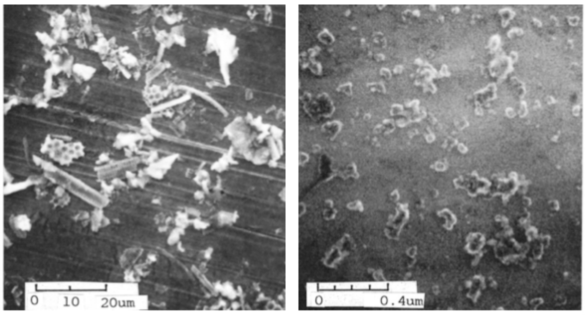
Fig. 6. Previous Seal Production Process

2.6 Unsuitable Rubber Filler

Fig. 7 shows filler photos of scanning electron microscope (SEM) in the silicone rubbers. The non-uniform contact property of the Rubber-P can be generated by a coarse filler. On the contrary, a fine silica filler of the Rubber-S can keep uniform contact as mentioned above. In addition, the Rubber-A, which contains 30% coarse filler has the highest fracture strength but causes distortion at a low compression. This indicates that the coarse filler mainly causes seal distortion and a high filler content causes strength reduction.

Therefore, it became clear that a quality control on both the filler size and the filler content are important for preventing coolant leakage.

Fig. 7. SEM Photos of Fillers in Rubber-P and Rubber-S (Ohkawa S. et al. 1993 [3])



Coarse Silica of Previous Rubber-P Fine Silica of Improved Rubber-S

2.7. Estimated Mechanism of Coolant Leakage by DAR

Through the DAR, we can estimate the coolant leakage mechanism as shown in Fig. 8. The leakage initially occurs the seal distortion, which is caused by coarse filler, and then the seal crack generates by rubber compression fatigue from excessive filler content. Since the type and the content of silicone filler in the silicone rubbers mainly affect the coolant leakage, adoption of the candidate Rubber-S, which contains

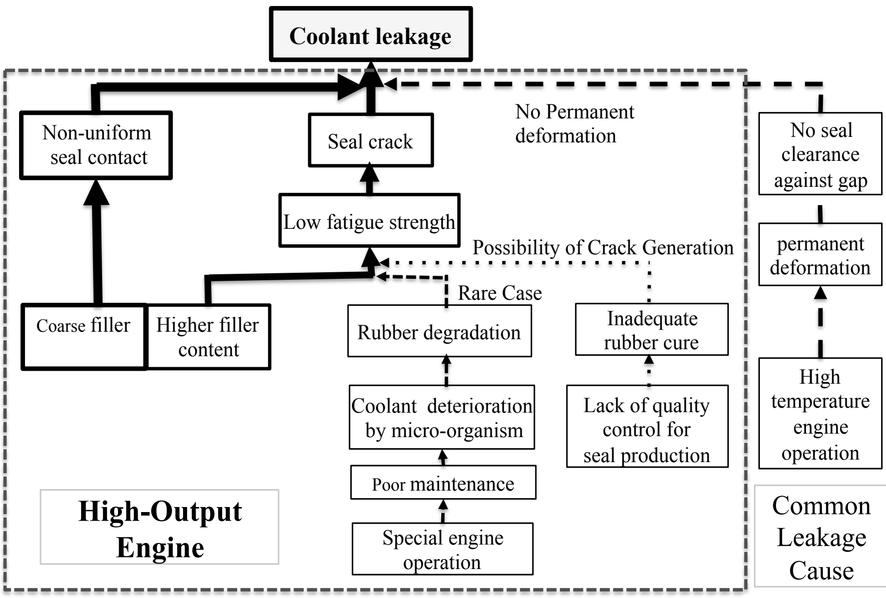


Fig. 8. Estimated Mechanism of Coolant Leakage

smaller volume of fine silica filler, becomes the best suitable resolution for improvement. The rubber degradation by the microorganism is a rare case. Other possible crack cause is by the lack of quality control of the seal production. Although a common leakage cause is seal permanent deformation, there is no permanent deformation problem of the coolant seal in the field.

3 VERIFICATION AND VALIDATION RESOLUTION PROCESS (VAR)

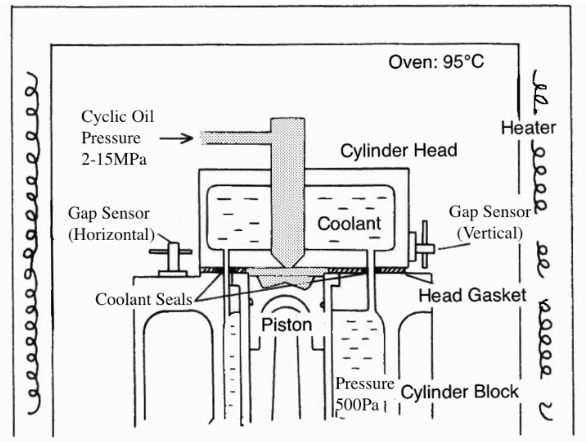
3.1 Methodology of VAR

Table 2 shows verification and validation (hatched parts) of the improved Rubber-S. The test methodologies are head-gasket unit tests by a newly developed tester, engine bench tests and field survey of modified engines, which adopted improved Rubber-S seals. Since agile countermeasure was requested, thorough validation: field survey, was conducted as soon as the verification was completed. To simulate the actual engine coolant seal conditions, seal verification tests were conducted by the head-gasket seal tester, which used the high-output engine assembly. Fig. 9 shows the tester schema. A cyclic hydraulic pressure is applied to a piston cavity. The cyclic pressure, which simulates engine firing, re-produces the largest displacement

Table 2. Verification and Validation Plan

No.	Critical Issues	Items for Countermeasure	Verification and Validation(hatched cell) Plan		
			Head Gasket Seal Tester	Engine Bench Test	Countermeasure and Field Survey
1	Only caused in improved engine	Improving uniformity of seal		✓	✓
2	Only caused in coolant seals	Adoption of high strength rubber	✓	✓	✓
3	Seal crack caused by coolant deterioration	Acid-proof rubber (Rubber-S)	✓	✓	✓
4	Inadequate seal production process	Change of seal production process			✓
5	Unsuitable rubber composition	Fine silica filler (Rubber-S)	✓	✓	

Fig. 9. Head-Gasket Seal Tester (S. Ohkawa et al. 1993 [3])



around the head-gasket in the engine tests. To adjust seal compression ratios, some head-gaskets having different thickness are used in every test.

3.2 Verification using Head-gasket Seal Tester

Fatigue test of seals to verify seal strength of improved Rubber-S. The unusual seal crack could be reproduced by this tester as shown in Fig. 10. The fatigue curves, drawn by the crack generation, were also obtained. The previous Rubber-P and the improved Rubber-S clearly shows different fatigue lives. The fatigue life of the Rubber-S is 10 times longer than that of the Rubber-P at the same compression.

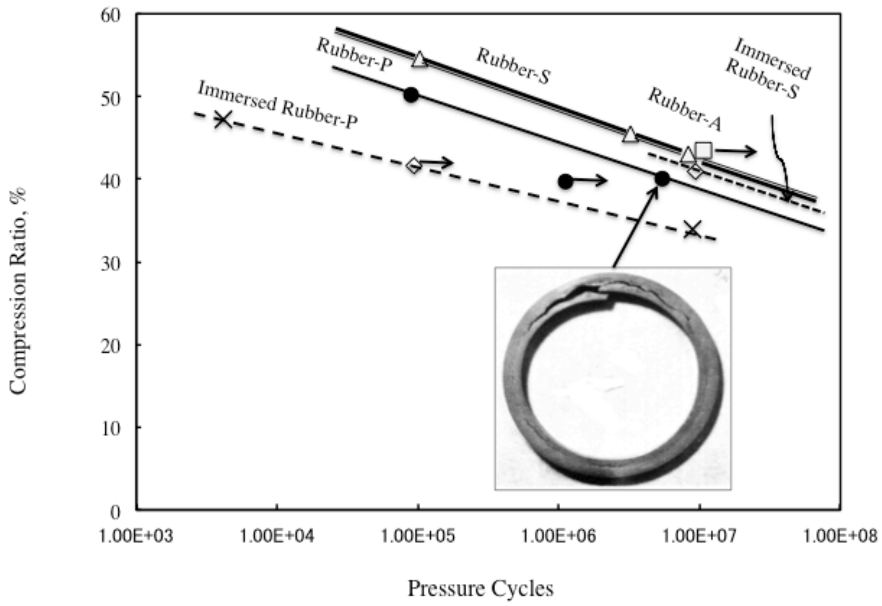


Fig. 10. Seal Fatigue Curves Obtained by Head-Gasket Seal Tester

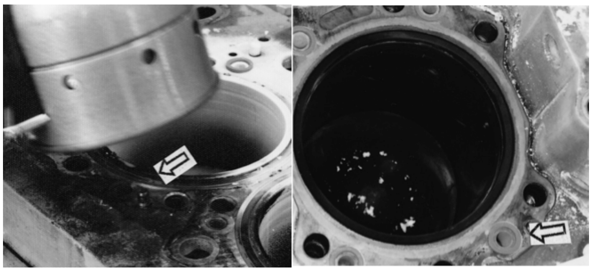
Fatigue test of acid immersed seals to verify effectiveness of acid-resistant polymer. After both Rubber-P and Rubber-S were immersed in an organic acid solution, the fatigue tests were conducted (Fig.10). The Rubber-P shows a large drop of decrease of the fatigue life. The fatigue life reduction of the immersed Rubber-S is small due to adoption of the acid-proof polymer. Therefore the fatigue life of the Rubber-S is about 100 times longer than that of the Rubber-P.

3.3 Verification Engine Bench Tests

Engine tests to verify the improved Rubber-S durability. By the 19 times engine tests from 50 - 2,000 hours, the previous Rubber-P seal have caused 5 times coolant leakages in the 10 tests at 100 - 2,000 hours, but the improved Rubber-S seals have never experienced leakage and crack in the 9 times tests from 50 - 2,000 hours. From the compression set data, it was confirmed that the Rubber-S has enough reserve to keep 10,000 hours life.

Verification of coolant leakage mechanism on seal distortion. On the bench engine test of the Rubber-P, we found that the coolant often leaks without seal cracking. To verify the leakage mechanism, the engine head was frozen with dry ice as soon as the leakage was detected. The cylinder head was removed and the leak was inspected using an ultraviolet rays as shown in Fig. 11. The leakage is detected clearly by the ultraviolet rays. The leaked seal did not generate any crack. Therefore it was proved that a leakage factor of the Rubber-P is unequal pressure distribution.

Fig. 11. Detected Coolant Leakage on Engine Bench Test
Right: Detected Coolant (arrow mark)
Left: Leaked Seal (arrow mark)
(S. Ohkawa et al. 1993 [3])



3.4 Countermeasure and field survey

The coolant seals of all kinds of engine were exchanged to the improved Rubber-S seal. All the engines, which caused coolant leakage in the field, were dismantled and were exchanged to the improved seals. As the results, the field coolant leakage problem is not reported in the field.

4 PERMANENT MEASURE OF COOLANT SEAL

All the high-output engines should be used for a longer period of time than U.S. final off-road emission regulation of 2014 [8] as shown in Fig.12. In order to obtain the longer MOL of the high-output engine production, the engine should withstand 5 times improvements/modifications for the emission regulations. Therefore a high-output engine, which attached exhaust emission reduction devices, was tested. As the result, the improved Rubber-S reduced the compression ratio down to 0%, and we have developed a further improved hydrogenated nitrile rubber [9, 10]: Rubber-T seal according to the DAR and the VAR as a permanent measure. Although a hydrogenated nitrile rubber shows shorter life than that of a silicone rubber in the air, we have found that a Rubber-T in the coolant extends its life 10 times longer than that of the Rubber-S. The timing of the permanent measure adoption is in the beginning

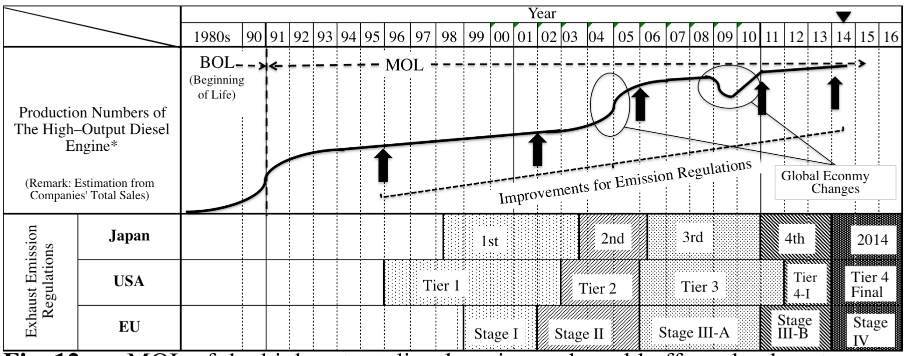
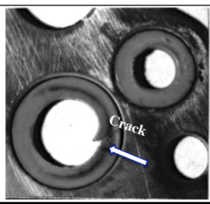
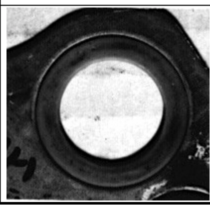
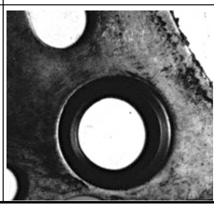


Fig. 12. MOL of the high output diesel engine and world off-road exhaust emission regulations [8]

of the MOL.

Table 3 shows accelerated high temperature test results using the head-gasket seal tester. The previous Rubber-P seal caused cracks. Although the improved Rubber-S seal did not cause any crack, its compression ratio reduced down to less than a lower limit. The Rubber-T could endure in this test and showed the highest compression ratio. However, we had to change the lower temperature range of the CONOPS from -50ºC to -30ºC because of poor low temperature property of the Rubber-T. We kept the Rubber-S as a specialized seal for cold weather regions.

Table. 3. High Temperature (155ºC) Test Results using Head-Gasket Seal Tester (Ohkawa S. et al. 1994 [4])

	Rubber-P	Rubber-S	Rubber-T	Remark
Test Cycles	4.7 x 10^6	1.2x 10^7		
Compression Ratio, %	1 (NG)	<1 (NG)	10 (OK)	Lower Limit: 5
Seal Condition				

5 CONCLUSION

Using the DAR of the system engineering, we can resolve the complexity composed of major causes and can clarify all the cause positions and relationships by analyzing the countermeasure of coolant leakage. We can confirm that the improved Rubber-S is the most appropriate countermeasure resolution and the Rubber-T is the best permanent measure resolution for the off-road emission regulations. The permanent measure resolution can extend the MOL of the high-output engine production and can withstand 5 times improvements/modifications for the emission regulations. Also we can recognize an importance to conduct thorough DAR even in the LCI and further down to the material composition.

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